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UV-Vis Spectrometer Assembly, Test and Calibration Guide

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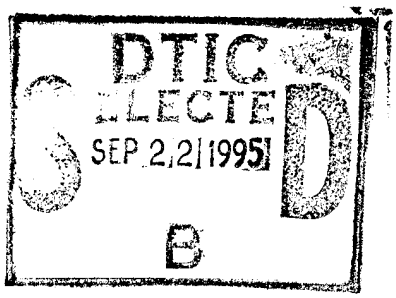

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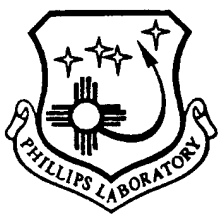

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FOREWORD

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13. ABSTRACT (MAXIMUM 200 WORDS)
This guide contains the information required to assemble, characterize, calibrate and test the Phillips Laboratory UV-Vis Spectrometer. The assembly is specific for the spectrometer; however, the characterization and calibration are more general and can be used as a guide for any spectrometer system. The guide gives direction and identifies calibration techniques that may be used, with the test set-up and results obtained on the Phillips Laboratory instrument. The guide also provides information on the collection and reduction of test data, using the techniques generated in the collection of the Aerojet 100 lbf test engine.

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FOREWORD

This document has been assembled not as a replacement of the manufacturers operational or instruction manuals but as a supplement to them. The document was written to provide some guidance and insight into the efforts required to complete the assembly and tests of the ultraviolet-visible (UV-Vis) Spectrometer Imaging System in a manner that will generate an understanding of the instrument and the data necessary to not only collect test data but also to successfully reduce that data. It is not the intent to say that the characterization tests, calibration tests, and data reduction listed in this document are the only ones required or that the techniques of data collection are the only correct techniques available. It is the intent that once read, in conjunction with the manufacturer's manuals, a thought process will be developed that will produce a detailed and careful examination of the test program to the extent that all required data for successful test data reduction will be identified along with the most effective technique available to generate the data.

ULTRAVIOLET-VISIBLE SPECTROMETER SYSTEM
INTRODUCTION

The objective of developing this ultraviolet-visible (UV-Vis) spectrometer system is to provide a portable stand-alone system to make high resolution spectral measurements simultaneously at multiple independent locations in a plume.

This documentation of the "Ultraviolet-Visible Spectrometer System" discusses everything about the system, including thorough descriptions of the hardware, set-up, characterization, calibration, data collection, and data reduction. The goal is to give users the tools they need to understand the system performance and to analyze the experimental data.

This work is broken down into the four sections listed below. These sections, together with the instrument manuals, meet the goal stated above.

Section I:	System Description
Section II:	System Set-Up
Section III:	System Characterization/Calibration
Section IV:	Data Collection/Reduction

Please note, this work is dynamic. As the system is upgraded, revisions to these sections will be made.

SECTION I: SYSTEM DESCRIPTION

Introduction

This section describes the system as configured. Along this line, many of the characteristics and specifications presented here are for this particular system. These values were obtained during the system characterization and calibration (see Section III: System Characterization/Calibration).

The system is broken down into its major components. These components are presented below in order from energy input to data acquisition. Each component is described in detail including where applicable, manufacturer, model number, description, upgrades, specifications, and figures. A simplified block diagram of the system is shown in Figure 1.

- Lens Assembly
- Fiber Optics Assembly
- Imaging Optics Assembly
- Filter Wheel
- Spectrograph
- Detector
- Detector Controller
- Gate Pulse Generator
- Data Acquisition System (Hardware)
- Data Acquisition System (Software)

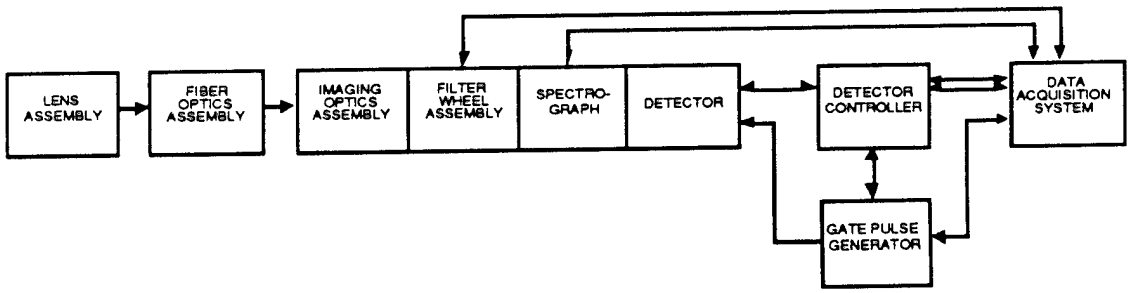

Figure 1: UV-Vis Spectrometer Imaging System

Lens Assembly

A simple lens assembly is used to collect energy from the target of interest. The assembly is a probe consisting of a compact tubular housing with a 12.7 mm diameter plano-convex lens which is mated to a fiber optic cable. By adjusting the distance between the lens and fiber optic cable, energy can be collected from a collimated path through the plume or a beam focused at any position in the plume. The lens assembly is illustrated in Figure 2.

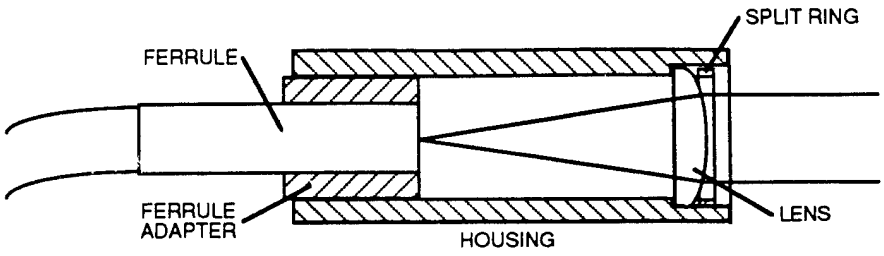

Figure 2: Lens Assembly

The lens is a fused silica plano-convex lens (Oriel Model # 41220). Table 1 gives the lens specifications.

Table 1

Lens Specifications

Material:	High purity UV grade fused silica
Transmission Range:	190 - 2500 nm
Diameter:	12.7 +0/-0.25 mm
Nominal Focal Length (@ 589 nm):	25.0 ±0.5 mm
Nominal Back Focal Length (@ 589 nm):	22.9 ±0.46 mm
Index of Refraction (@ 589 nm):	1.4584
F/#:	2
Center Thickness:	3.0 ±0.25 mm
Edge Thickness:	1.0 ±0.25 mm
Coating:	None

The probe housing is a modified black anodized aluminum cylinder (Oriel Model # 77645). The housing is approximately 39.6 mm long by 16 mm in outside diameter. A split ring holds the lens against a shoulder.

The ferrule adapter is also made of black anodized aluminum (Oriel Model # 77666). It has an outside diameter of 11 mm and an inside diameter of 6.43 mm. Its length is 12.2 mm. The ferrule adapter is attached to the fiber optic cable with two hexagon set screws, located 90° apart. Up to two hexagon set screws can be used to lock the ferrule adapter/fiber optic cable in the probe at the desired focus.

Fiber Optics Assembly

The fiber optics assembly transmits the collected energy from the lens assembly to the spectrometer. This custom designed assembly was produced by C Technologies, Inc. The fiber optics assembly is shown in Figure 3.

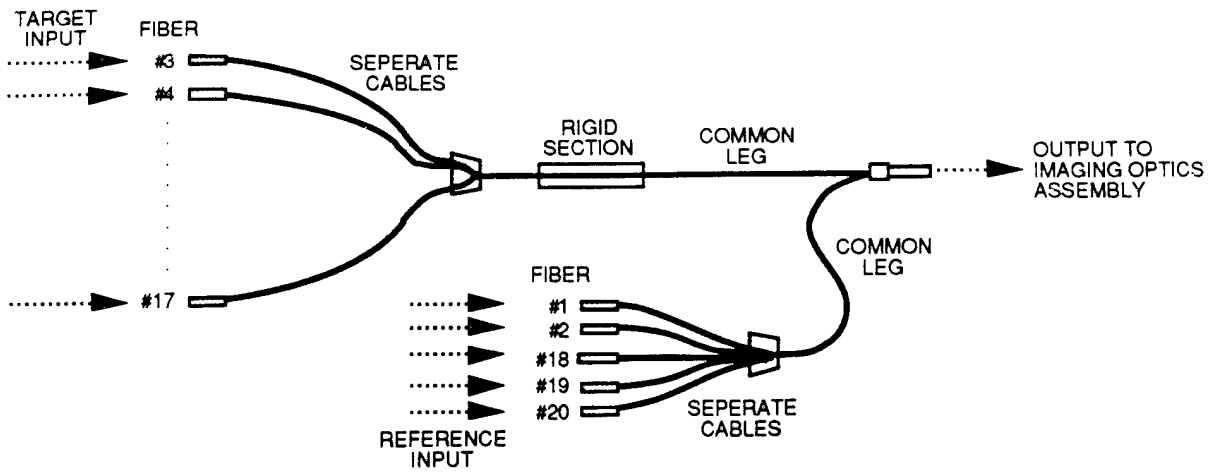

Figure 3: Fiber Optics Assembly

The assembly is composed of two sections with a total of twenty input fiber optics cables. The first section transmits energy from the target while the second transmits energy from reference sources. All energy is transmitted using continuous UV grade fused silica optical fibers. The fiber optics assembly specifications are given in Table 2.

The target section is composed of fifteen separate fiber optics cables that merge together to form a common leg. Each cable contains a single optical fiber and is tipped with an aluminum ferrule. These cables come together to form a common leg. The common leg has a rigid section that can be used to provide a seal through a test chamber wall.

The reference section is composed of five separate fiber optic cables. These cables are used to transmit energy from spectral and/or intensity reference sources and allow the system to simultaneously collect calibration and test data. Each cable again contains a single optical fiber and is tipped with a ferrule. The separate cables also merge together to form a common leg.

Table 2

Fiber Optics Assembly Specifications

Optical Fiber Diameter:	100 μm
Optical Fiber Material:	UV grade fused silica
Jacket:	Flexible stainless steel
Continuity:	Continuous input to output
Target Section:	
Number of Fibers:	15
Ferrule:	50.8 mm long by 6.27 mm dia
Length of Separate Cables:	250 ±5 cm
Length of Common Leg:	135 ±10 cm
Total Length:	385 ±15 cm
Rigid Section Length:	15 cm
Rigid Section Location:	30 ±5 cm from separate cables

Table 2 (Cont.)

Reference Section:	
Number of Fibers:	5
Ferrule:	25.4 mm long by 6.27 mm dia
Length of Separate Cables:	50 +5/-0 cm
Length of Common Leg:	40 +5/-0 cm
Total Length:	90 +10/-0 cm

The two common legs described above are joined at the output connector. This connector is sized to mate with the Acton Imaging Optics Assembly (Figure 4).

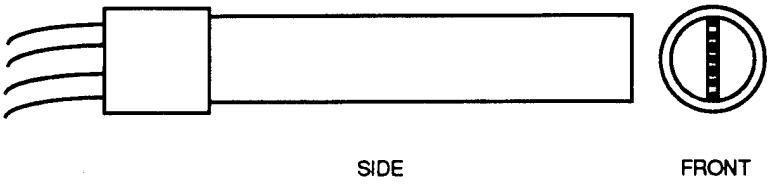

Figure 4: Output Connector

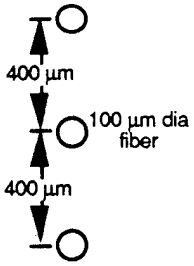

Figure 5: Output Array

At the output, the twenty optical fibers are arranged in a one-dimensional vertical array with 400 micron center-to-center spacing (Figure 5), providing a height of 7.7 mm. The reference optical fibers are the top- and bottom-most fibers in this array. Due to these locations, the energy from these fibers is expected to suffer the worst spectral and spatial degradation in the spectrometer. However, since this energy will typically be from known sources, it can be used to determine a measure of the test data quality.

Imaging Optics Assembly

An Acton Research Corporation (ARC) imaging optics assembly is used to optically match the fiber optics assembly output to the spectrograph input. The matching preserves the image integrity of the transmitted energy with minimal spatial distortion--allowing the energy from each optical fiber to remain vertically separate through the spectrograph to the detector array where the fibers are re-imaged. This vertical separation is characterized in "UV-Vis Spectrometer System, Section III: System Characterization/Calibration." However, to accomplish the optical matching, some energy is lost. This transmission loss is approximately 10%. A simple diagram of the imaging optics assembly is shown in Figure 6.

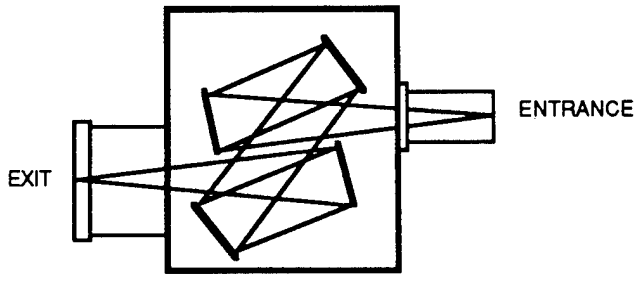

Figure 6: Imaging Optics Assembly

Filter Wheel Assembly

A filter wheel assembly provides the means to eliminate any unwanted second order radiation. This assembly is a ARC Model FA-448-3, Motorized Order Sorting Filter Assembly. It holds up to six filters and consists of a filter wheel, stepper motor, and controller. The photo in Figure 7 shows the components. The assembly is mounted directly to the entrance slit housing of the spectrometer.

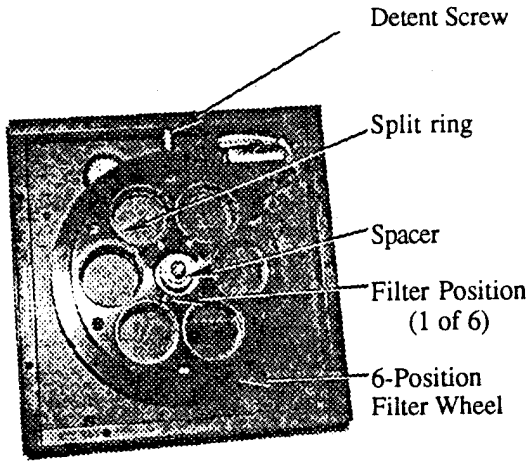

Figure 7: Filter Wheel Assembly

The six filters are 25.4 mm in diameter and are held in place with split rings. The amount of time it takes to rotate the filter wheel between adjacent filter positions is approximately 1.4 seconds. The wheel rotates in both clockwise and counterclockwise directions, using the shortest path to the next filter position. Filter positions can be selected manually through the use of a thumb wheel on the controller or automatically by a computer via an RS-232 serial line. Communication through the RS-232 port is at 9600 baud, no parity, 8 data bits, 1 stop bit, and 1 start bit. Voltage to the controller is 115 VAC.

The filters consist of two sets of two Schott glass order sorting filters with cut-on wavelengths (50% transmission) of 299 and 475 nm. A third set of two filters with a cut-on wavelength of 138 nm was also added. The filter positions in the filter wheel are given in Table 3. These positions were selected to minimize the filter wheel motion and , therefore, the time required to change filters.

The third filter set was added to achieve a single system focus. Since the system must be manually focused, only one focus position can be used in each test for all wavelengths. When a filter is introduced into the light path, the focus position changes as a function of the filter's index of refraction. focusing the system with an open filter position (typically used for wavelengths in the 180-360 nm range) and then changing to the first order sorting filter results in a substantially unfocused image. To compensate for this effect, the third set of barium fluoride filters was

installed for use in the 180-360 nm range. This filter presents the best combination of (in priority) UV transmission, indices of refraction, thickness, resistance to high energy radiation, and susceptibility to attack by water. With the indices of refraction of the three filters approximately the same (in their respective wavelength regions), a single focus can be obtained for all wavelengths.

The specifications for all three filters are listed in Table 4. For more information on the filter wheel assembly, see the "Action Research Corporation SpectraPro-500 Operating Instructions."

Table 3
Filter Positions

Filter Wheel Position	Filter Cut-On(nm)
1	138
2	299
3	475
4	138
5	299
6	475

Table 4
Order Sorting Filter Specifications

Filter	Model	Cut On* (nm)	Range** (nm)	Thickness (mm)	Parallelism (min)	Reflection	Index of Refraction λ(nm)	n
BaF2	Janos A0705-352	140	180 - 360	3 ±0.25	3	NA	260	1.51
							300	1.50
							360	1.49
Schott (WG295)	Oriel 51225	299	325 - 580	3 ±0.15	2	0.92	334.1	1.54
							587.6	1.52
Schott (GG295)	Oriel 51290	475	495 - 930	3 ±0.15	2	0.91	587.6	1.54
							852.1	1.53

* 50% transmission
** 95% internal transmission

Spectrograph

The spectrograph is an ARC SpectraPro-500, Model 408i. This system is a Czery-Turner spectrograph with a 0.5 m focal length, and consists of two components: the spectrograph and a remote scan controller. A simple diagram of the spectrograph is shown in Figure 8 and the specifications are listed in Table 5.

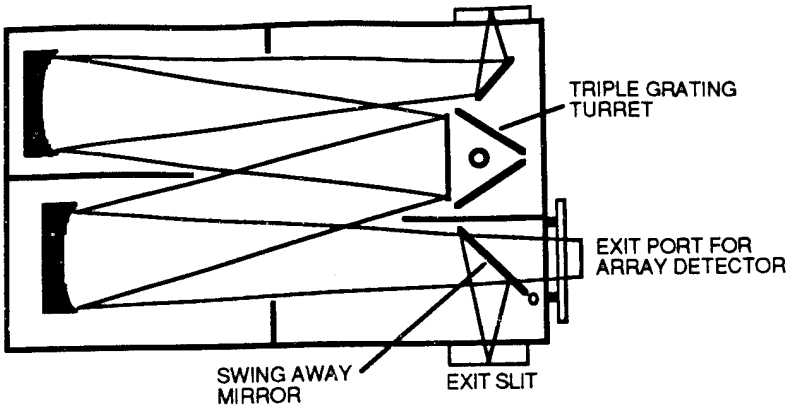

Figure 8: Spectrograph Schematic

Table 5
Spectrograph Specifications

Focal Length:	0.5 m
Optical System:	Computer Optimized Czerny-Turner
Aperture Ratio:	f/6.9
Wavelength Range:	See Grating Information below
Wavelength Accuracy:	±0.2 nm
Wavelength Reproducibility:	±0.05 nm
Entrance Slit Width:	10 to 3000 μm
Entrance Slit Height:	10 mm
Exit Slit Width:	10 to 3000 μm
Exit Slit Height:	10 mm
Exit Port Focal Plane:	25 mm wide by 20 mm high

The remote scan controller controls all spectrograph scanning functions and turret, grating, and wavelength selections. All information on the installed gratings is programmed into the controller. This information plus the current operating settings are displayed on the controller's LCD display. The spectrograph controller can be operated manually through the controller keypad or by computer via an RS-232 line. The communication through the RS-232 is at 9600 baud rate, no parity, 8 data bits, 1 start bit, and one stop bit.

The spectrograph has one entrance and two exit ports. The entrance port is a manually operated slit with a bilaterally adjustable slit width. The exit ports consist of one exit slit and one port for an array detector. The exit slit is similar to the entrance slit. The exit port provides a focal plane for a two-dimensional detector array. Adjustable external flanges at the exit port allow the spectrograph to be used with a variety of standard detectors. These flanges permit rotation, tilt, and axial motion for alignment and focusing. Exit port selection is made by using a manual externally controlled swing away mirror.

The spectrograph gratings are installed on removable triple grating turrets. This system was acquired with six gratings installed on two turrets. Grating selection (for the installed turret) is done through the remote scan controller discussed above; it takes approximately 50 sec for the

spectrograph to change gratings. Grating specifications are listed in Table 6, while the system performance is described in Table 7.

Table 6

Grating Specifications

Turret #	Grating #	Grating Spacing (gr./mm)	Blaze Wavelength (nm)	Usable Range* (nm)
1	1	3600	250	300-500
	2	2400	240	
	3	300	300	
2	4	1200	300	
	5	600	300	
	6	147.5	300	

* Minimum--efficiency ≥10%

Table 7

System Performance

Grating #	Grating Spacing (gr./mm)	Linear Dispersion (nm/mm)	Maximum Scan Speed (nm/min)
1	3600	0.3	250
2	2400	0.5	375
3	300	6.4	3000
4	1200	1.5	750
5	600	3.1	1500
6	147.5	13.2	6000

The spectrograph uses 120 VAC. Power is provided to the spectrograph through the remote scan controller. No heat generating elements are located in the spectrograph, minimizing thermal distortion.

Detector

The system uses a Princeton Instruments (PI) Model ICCD-576S/B detector. This detector has a cooled CCD, fiber-optically coupled to a gate-able UV-enhanced image intensifier. A simplified schematic of the detector is shown in Figure 9 and the detector specifications are presented in Table 8.

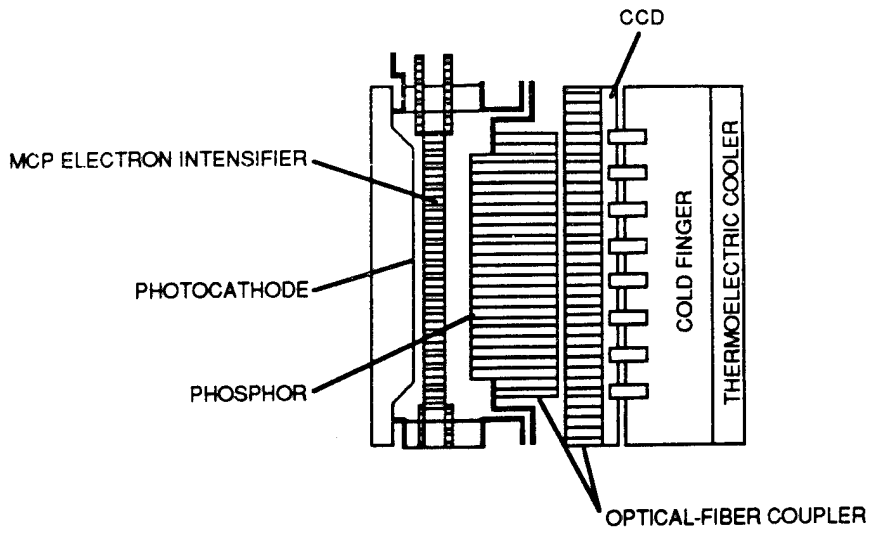

Figure 9: Detector Schematic

Table 8

Detector Specifications

Spectral Range:	~180 - 880 nm (see Figure 10)
Quantum Efficiency:	13% @ 250 nm
CCD Array:	Thompson CSF Model 788F0-2
Array Dimensions (column x row):	576 x 384 pixels
Pixel Dimensions:	23 m x 23 m
Spatial Resolution:	<3 pixels @ FWHM of spectral line
Geometric Distortion:	<1 pixel
Dynamic Range:	14 bits
Response Linearity:	>1% for upper 95% of range <1% for bottom 5% of range
Uniformity of Response:	3.8% across the array
Sensitivity:	Variable up to 100 counts/photoelectron
Dark Charge:	2 counts/pixel/second
Equivalent Brightness Emission (EBI):	0.1 counts/pixel/second
Gating On/Off Ratio:	$>5 \times 10^6$:1
Gain Range:	1×10^4

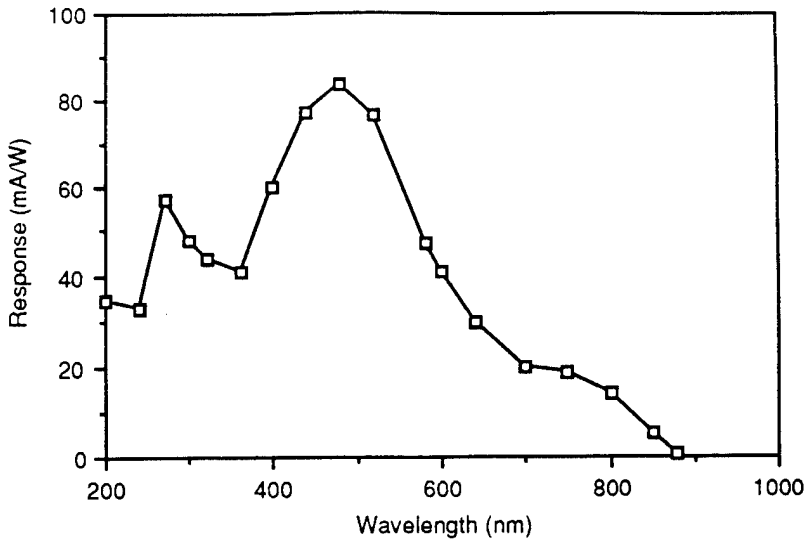

Figure 10: Measured Photocathode Responsivity

The intensifier is an 18 mm diameter proximity focused gate-able microchannel plate (MCP) intensifier, with a UV-enhanced photocathode. The photocathode responsivity is shown in Figure 10. This intensifier can be gated by a gate pulse generator or run in shutter mode, where the detector is on continuously except during read-out of the array. The shutter close and open times are relatively long: 6 ms and 5 ms, respectively. Due to the large size of the photocathode, some iris-effect may be apparent when the intensifier is gated. The gate/shutter modes are manually selected with a switch located on the rear of the detector. The intensifier gain can be manually adjusted by varying the voltage across the MCP using a ten-turn potentiometer, also located on the rear of the detector.

Detector cooling is provided using two methods: 1) thermoelectric (TE) cooling with water circulation and 2) coolant circulation. TE cooling with water circulation is used to cool the CCD array. This cooling is controlled by the detector controller and is adjustable down to -35 °C by varying the power to the TE coolers. The heat generated by the TE coolers is removed through the use of room temperature tap water circulation (1.0 liter/minute). The second cooling system--coolant circulation--is optional and is used to cool the intensifier photocathode. This will cool the photocathode down to approximately 12 °C above the coolant temperature (Tpc = Tc + 12 °C). This cooling can reduce EBI (shot noise due to thermally generated photoelectrons from the photocathode) by a factor of approximately 50. The coolant is a 50/50 mixture of ethylene glycol (antifreeze) and water. It is circulated through a direct contact cooling jacket (PI Photocathode Cooler Model CPC-100) mounted around the intensifier. Cooling and circulation are provided by a NESLAB Instruments, Endocal RTE-110, Refrigerated Bath/Recirculator.

The detector must be continuously purged with dry air or GN2 (300-500 ml/min) to prevent condensation on the intensifier.

More information on the detector, photocathode cooler, and coolant recirculator is available in the following sources: "PI Detector Manual" and "Endocal RTE-Series Refrigerated Bath/Recirculator".

Detector Controller

The detector operation is controlled through a detector controller. The controller, a Princeton Instruments (PI) ST-130 Type 2 Detector Controller, interfaces between the data acquisition system and the detector. It provides power to the detector and temperature regulation to the CCD array. In addition, it coordinates data collection per instructions from the data acquisition system: it sets the detector exposure times (shutter mode), triggers the gate pulse generator (gate mode), reads-out the CCD array, digitizes the data, and transmits the raw data to the data acquisition system. Table 9 lists the detector controller specifications.

Table 9

Detector Controller Specifications

Temperature Control:	-35 °C (with detector water circulation)
Temperature Stability:	±0.05 °C
A/D Converter Range:	14 bits
Linearity:	better than 1%
Exposure Times -Shutter Mode:	5 ms to 23 hrs, 5 ms increments
- Gate Mode:	See Gate Pulse Generator information
Accumulator Memory Width:	32 bits
Readout Rate:	25, 50, 100, or 200 KHz (user selectable)
Internal Boards:	
Analog Board:	PI 1700-0100 Rev C?
Direct Memory Access (DMA) Board:	PI 1700-0115 Rev B

The detector controller uses 120 VAC, 2 A power. It is rack mounted with the gate pulse generator in a portable case.

Gate Pulse Generator

The detector can be gated by using the gate pulse generator, a Princeton Instruments PG-200. This programmable gate pulse generator is used for short detector integration periods. It serves two major functions--generating gate pulses and providing a timing source and delays. In this system, the second function is not used. The generator can be programmed through the front panel or remotely by serial interface with the data acquisition system. It is triggered by the detector controller, and communication to the detector is accomplished via a BNC cable (3 ft max, 50 Ohm impedance). Specifications for the gate pulse generator are presented in Table 10.

Table 10

Gate Pulse Generator Specifications

Accuracy	±3 ns (for minimum time interval)
Precision	± 1 ns or 0.1% (whichever is greater)
Jitter	<0.5 ns or 0.05% (whichever is greater)
Temperature Drift	< ± 1 ns or 200 ppm per °C (whichever is greater)
Gate Pulse Magnitude	-200 ± 20 V
Pulse Width Range	3.5 ns - 80 ms

The gate pulse generator and detector controller are rack mounted together in a portable case. More information is available in the gate pulse generator manual.

Data Acquisition System (Hardware)

An IBM-compatible personal computer is the core of the data acquisition system. The PC is a Gateway 2000 486DX with several upgrades. This PC both controls the experiment (via the detector controller) and saves the raw experimental data. The link between the computer and the detector controller is accomplished using two 50-conductor ribbon cables between a custom PI buffer board in the computer and a Direct Memory Access (DMA) board in the controller. This link allows rapid data transfer between the controller and the computer, that is digitized data from controller to RAM and to hard disk. The computer is also linked to the gate pulse generator, spectrograph scan controller and filter wheel controller via RS-232 serial lines. These links enable the computer to reprogram the gate pulse generator settings (e.g. the pulse width), change grating settings, and rotate the filter wheel during the experiment. All the data acquisition system hardware is rack mounted in a transportable case. The hardware specifications are given below.

Table 11

Data Acquisition System Hardware Specifications

RAM:	64 MB
Cache:	64 KB
Microprocessor/Math Co-processor:	80486DX
CPU Clock Speed:	33 MHz
Data Bus Size:	32 bits
I/O Ports:	3 Serial/2 Parallel
Expansion Slots:	8 16-bit slots
Internal boards:	
Buffer Board:	Princeton Instruments 1700-0050 Rev B
I/O Card:	DFI Model DIO-500 Rev 6 (2 Serial/2 Parallel) IDE Hard Drive and Floppy Disk Controller
SCSI Drive Adapter Card:	Iomega PC2B/50 Host Adapter
Color Video Graphics Board:	ATI, VGA Wonder (1024x768/16 colors)
Internal Hard Disk Drive:	200 MB, Western Digital
Internal Floppy Disk Drives:	1.44 MB 3.5", Epson 1.2 MB 5.25", Epson
External Removable Cartridge Drive:	Iomega Bernoulli Transportable 90-MB Pro
Color Graphics Monitor:	CrystalScan 1024NI (1024x768)

Data Acquisition System (Software)

The spectrometer system is controlled by Princeton Instruments' CCD Spectrometric Multi-channel Analyzer (CSMA) software package. CSMA is a software package that can acquire, display, store, process, and plot data from the spectrometer system. It was designed to interface with the detector controller and other system hardware, including the gate pulse generator, spectrograph scan controller, and filter wheel controller.

CSMA is built around a high-speed user-programmable environment called Spectrum Basic, a software language similar to BASIC. Spectrum Basic allows sequences of commands to be preprogrammed for a given experiment. Coupled with the software's ability to control much of

the system hardware, this gives the data acquisition system the flexibility to use a variety of instrument settings in a single test.

SECTION II: SYSTEM SET-UP

Introduction

The UV-Vis Spectrometer System must be assembled as directed in the instrument manuals. All manuals should be reviewed prior to system assembly. Once assembled, the initial alignment and adjustments can be made.

System Assembly Adjustment and Alignment

After installing the detector module onto the exit slit of the monochromator, it is necessary that the detector array be aligned with the entrance slit and exit plane to assure that a single column of the array contains the same spectral data from the top of the column to the bottom. It is also necessary to focus the monochromator exit image onto the detector array to obtain the maximum spectral resolution as well as providing a sharp vertical image for spatial image separation.

Detector Initial Alignment

After assembly of the detector array to the monochromator the detector alignment procedure is performed. The rotational alignment is accomplished using the Hg lamp as the source. The energy level of the Hg source is high and it will be necessary to insert a double or triple layer of paper between the Hg source and the entrance slit to stay below saturation. Alignment procedures are as follows:

1. Install the Hg source to the entrance slit with multiple layers of paper between the source and entrance slit.
2. Set the monochromator on grating 4 (1200 gr/mm).
3. Set the grating controller to collect energy on the 435.8 nm Hg line.
4. Set the data collection system to bin 5 rows at the top, middle and bottom of the detector array.

The data collection screen is now set to show three traces of the binned data with a peak at the detector position of the 435.8 nm Hg line. This is shown in Figure 11 below:

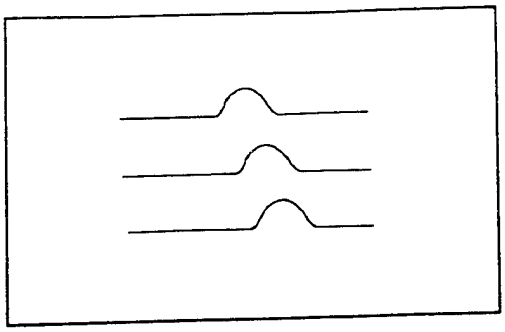

Figure 11: 435.8 nm Hg Line at Three Vertical Focal Plane Positions

The detector assembly is now rotated until the peaks of all three binned data sets are aligned on the same column pixel number. The focus adjusting screws are then adjusted to provide minimum pixel count between fixed amplitude points on the curves. This provides the initial alignment. Final rotational alignment and focus will be accomplished after the installation of the imaging optics and probes. Some system characterization must be accomplished prior to the installation of the entrance imaging optics and collection probes.

Probe Assembly

Probe assembly and adjustment are accomplished with the use of a laser source illuminating the fiber optics output. Figure 12 shows the assembly and adjustment configuration.

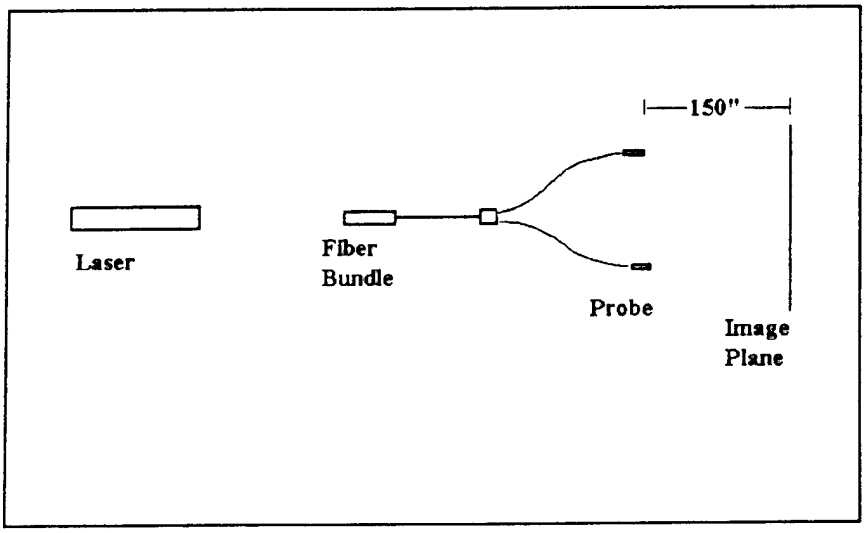

Figure 12: Probe Assembly and Adjustment Configuration

The procedures are as follows:

1. The ferrule and ferrule adapters are assembled.
2. The lenses are installed into the housings.
3. The probe-fiber is adjusted for best image at the image plane.
4. The spot size is measured to produce the same size image on all probes.
5. The ferrule adapters are rotated in the housing to set a uniform height probe to image.
6. The complete lens assembly is rotated in the assembly holder and the amount of image motion is noted.
7. Assemblies with image motion of greater than 1 1/2", at the image plane over a housing rotation of 360 degrees are re-adjusted by rotating the ferrule in the ferrule adapter and then re-measured.

All assemblies are adjusted to produce image motions of less than 1 5/8". The image quality of probes 11 and 14 was poor. Probe 11 produced significant speckling with a 5/8" image center. Probe 14 showed coma at 135 degrees, with 0 degrees being the top of the image. Prior to data collection, all probe, split ring, and lens assemblies must be checked to assure proper seating of the lenses.

Turret Grating Alignment

Grating alignment in each turret was accomplished using the ARC alignment mask and the procedures, which were developed and provided by ARC, and recorded in the instrument manual.

Imaging Optics Assembly/Fiber-Optics Bundle

The fiber-optics bundle output connector is inserted into the imaging optics holder until 0.495 to 0.496 inches of fiber-optics bundle remains outside of the holder (see Figure 13). This provides focusing of the fiber-optics output through the imaging optics. The fiber-optics bundle is rotated until the output of probes 1 and 20 were maximized. This required the adjustment of the imaging optics horizontal position to provide horizontal alignment of the fiber-optics arrays vertical alignment with the entrance slit. The imaging optics vertical adjustment is then used to position the center probe output onto the center of the exit focal plane detector array.

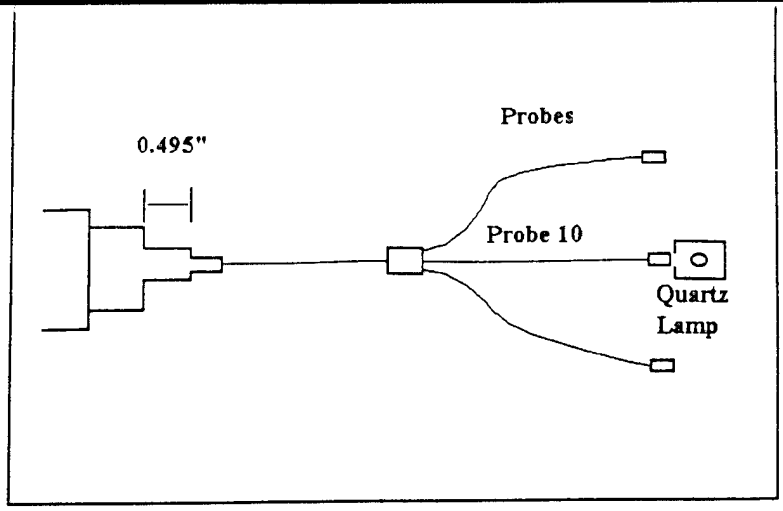

Figure 13: Fiber-Optics Bundle/Image Optics Holder Assembly

Final Detector Alignment

With the completion of the system assembly the final detector alignment can be completed. The final detector alignment and focus are conducted with the following set-up and procedures.

1. The source is the quartz lamp as an input to a probe at or near the array center.

2. The resulting line image is evaluated for starting and ending pixel rows and line image width.

3. The detector assembly is rotated to place the center of the line image on the same rows on the left and right side of the focal plane.

4. The spectrometer focusing mirror is adjusted to provide the same line image width in number of rows on the left and right side of the focal plane.

5. The detector assembly focus is adjusted to provide a minimum of illuminated pixel rows at the left, right and middle of the focal plane.

This alignment procedure showed that the spectrometer did not have a flat focal plane image as had been specified. This makes the data inversion and interpretation somewhat more difficult.

The UV Imaging Spectrometer hardware is now assembled and ready for characterization and calibration.

Data Acquisition

Prior to the acquisition of any data whether it is for alignment, characterization, calibration or test, the data acquisition system must be set up to collect and store the data. There are a number of steps to be completed before the data acquisition process can begin. These steps are as follows:

1. A memory block must be declared for the set of collected data frames. MSDOS must be used to reserve the required RAM, random access memory, for the data.

2. The CSMA software must be run. With CSMA operating the communication parameters must be set on the serial ports for grating controller and filter controller. The ports must then be initialized to communicate with the controllers using the CSMA menu.

3. A series of hardware initializations must be accomplished. The turret and grating to be used must be installed. The desired CCD data region must be initialized by binning both the spatial and spectral regions. The filter wheel controller must be set to provide the filter for the first data frame to be collected. This can be achieved either by a Spectrum Basic Program or command line entries in the CSMA program.

4. The grating is now moved to the wavelength desired for the first data frame to be acquired. An acquired data set code is now inserted, 1 or 2 characters, into the filename section of the data acquisition menu. The integration time of the first data frame is set and the data acquisition software is executed.

The data acquisition software must be assembled guided by a set of instrument and data parameters. The acquisition software is generated through the following series of steps and event identification.

1. To initiate the software it is necessary to declare, (1) an array that stores the center wavelengths of the spectral windows in which the data will be collected, (2) an array with elements containing the integration times to be used at each data window, and (3) the grating number that is being used (this number is unique for each grating and will be used in the construction of the file names of each collected data frame). Finally, (4) an array that can store the data frame based on the dimensions dictated by the size of the frames being collected. This size is based on the number of pixels of the CCD within the data frame to be acquired.

2. It is necessary to determine the starting RAM address of a preserved memory block. This block will be used to store multiple data frames. The computer memory at this starting address and higher are then used for acquired data storage and the lower addresses are for the computer operating system, CSMA program, device drivers, and other software.

3. Suspend all micro programming and clear the screen.

4. Wait for the TTL signal trigger to start the data collection process.

5. Start the detector controller to collect a data frame. When data collection is complete, stop the detector controller and transfer the data from the data acquisition board buffer to RAM. Increment the RAM address by the data frame size to the desired spectral interval of the new data frame and the corresponding change in the filter.

6. Upon completion of the data collection the data must be saved to the computer disk. The file names of each data frame should include an experiment code, grating number, collected data frame sequential number, and center wavelength for ease in data tracking and identification. With the pointer set at the starting memory address open a file with the appropriate file name and transfer the data from RAM to disk. Header information must also be saved in the file. This header contains information to identify the data collection parameters such as exposure time, CCD array dimensions, data frame dimension, type of data, and data size per pixel. The starting memory address is then incremented by a data frame dimension to the starting memory address of the next data frame and the process is repeated for all collected data frames.

The data acquisition software and process is ready to begin characterization, calibration, and test data collection. For additional information review the manufacturers software and hardware operational manuals.

SECTION III: CHARACTERIZATION/CALIBRATION

Introduction

There are a number of relationships in the operation of the UV-Vis Imaging Spectrometer that require characterization, that is the determination of how the system functions. These tests are separate from the calibration in that the results are not necessarily used to reduce the collected data but may be used to determine how and what data are required to be collected. These tests along with the system calibration fully define the system's performance capabilities. This section will cover those test and test results which both characterize and calibrate the system.

System Noise

The final operational limitation of a system is dictated by the system noise. Noise data were taken with the entrance slit covered. Data were collected as a function of system gain, image intensifier temperature, and exposure time. The tests' data were taken with the following parameter limits:

1. Gains varying from 0 to 10 in increments of 1.
2. Exposure times varying from 5 msec to 10 minutes.
3. Temperatures of -20, -10, 0, 10 and 20 degrees C.

Data sets were collected at all gains with temperatures of 20 and -20 degrees C for exposure times of 5, 250 and 1000 msec.

Data sets were collected for the full exposure time range for -20 and 20 degrees C at a gain of 10, and at 20 degrees C at a gain of 8.

For evaluation of repeatability, data sets were gathered at a gain of 8 with an exposure time of 250 msec, and a temperatures of 20 and -20 degrees C.

Data sets were gathered at 10, 0 and -10 degrees C for a gain of 10, and exposure times of 500, 1000, 5000 and 50000 msec.

The statistics of each 576 x 348 pixels frame were generated as the mean and standard deviation, in counts, of each frame of data, taken at a gain of 8 and exposure time of 250 msec. The mean is shown in Figures 14 and 15. This shows the instrument noise to be stationary. The mean and median of the noise frequency are equal which validates the use of standard statistical methods for defining the noise characteristics. In Figure 14, the mean varies by 0.08 counts out of 101 at an image intensifier temperature of 20 degrees C and 0.03 counts out of 101 at a temperature of -20 degrees C. This variation is well within the standard deviation of 1 to 1.4 counts. Figure 15 shows the instrument performance at an exposure time of 60000 msec. As can be expected the noise of the system increases with exposure time as the CCD array collects charge for a longer time

period. The variation in the mean in the ten frames taken at 60 seconds in 1.4 counts out of 276 counts. This is still well within the standard deviation of 22 counts. The data in Figure 15 has a positive slope indicating that there is insufficient data to determine the actual mean of all frames over time, or an instrument parameter which drives the output did not stabilize. The total variation is less than 0.5% and the exposure time of 60 seconds is longer than most anticipated test data collection times. This drift must be noted for any future data collections and the collection exposure times kept below this 60 second limit or the data corrected for the drift if it is significant in relation to the data signal strength.

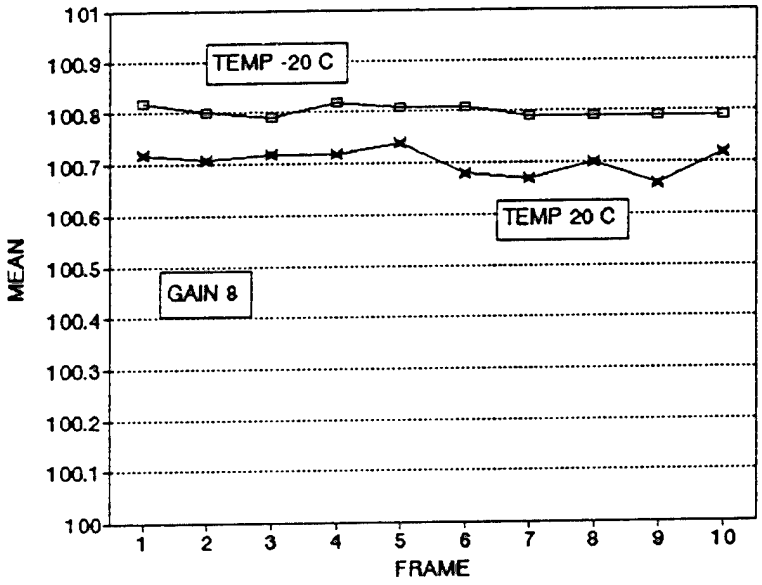

Figure 14: System Noise Stability. Exposure Time 250 msec.

Figures 16 and 17 show the system noise mean and standard deviation as a function of gain for exposure times of 5 msec, 250 msec and 1 sec. From other data the apparent intermittent anomaly, shown in Figure 16, at a system gain of 10 is valid. To date, all test data have been gathered at a gain of 7 which is well below the operating region at a gain of 10. If the higher gains are to be used, the reason for this anomaly and its impact on the data must be understood. As can be expected, Figure 16 shows no change in the mean as a function of gain through a gain of 9. The gain adjusts the response of the image intensifier. With no signal coming into the image intensifier, one would not expect a change in the noise mean. A change in standard deviation, or noise variation, can be expected and is shown in Figure 17.

The variation in the mean and standard deviation as a function of exposure time in msec for a gain of 8 are shown in Figures 18 and 19. The data in Figure 18 shows a bias which varies as a function of exposure time. This bias must be removed from the data prior to reduction and interpretation.

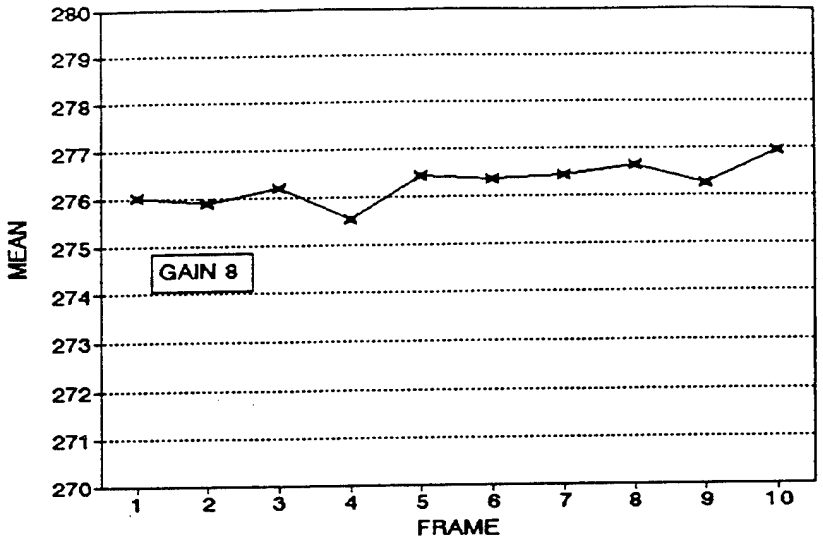

Figure 15: System Noise Stability Exposure Time 60 Sec

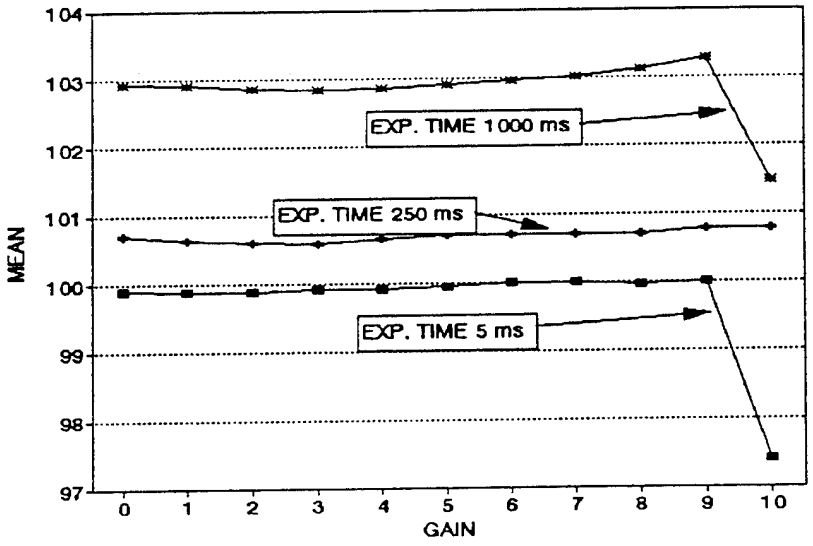

Figure 16: System Noise Mean as a Function of Gain

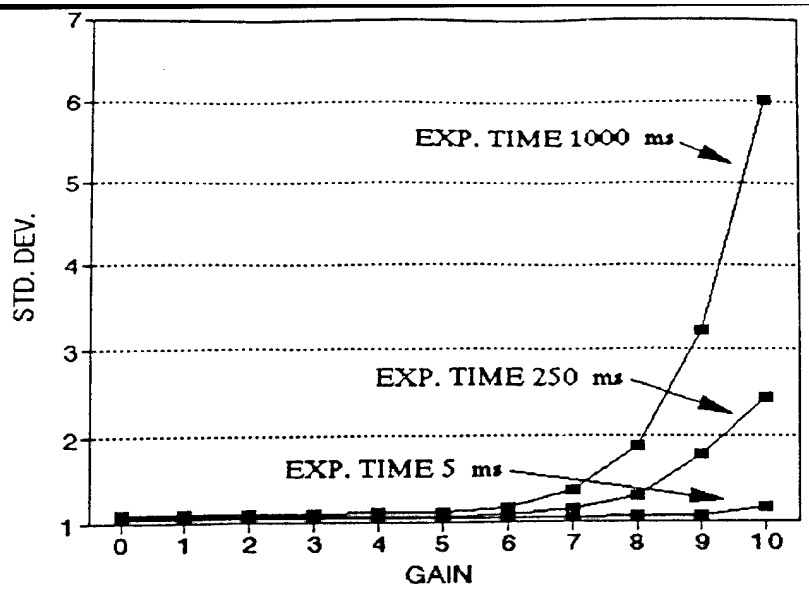

Figure 17: System Noise Standard Deviation as a Function of Gain

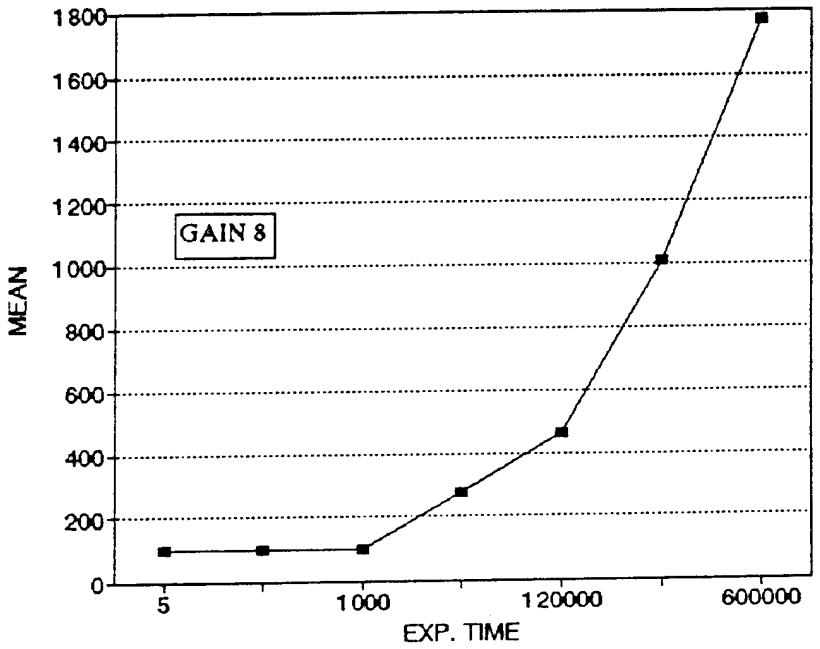

Figure 18: System Noise Mean as a Function of Exposure Time

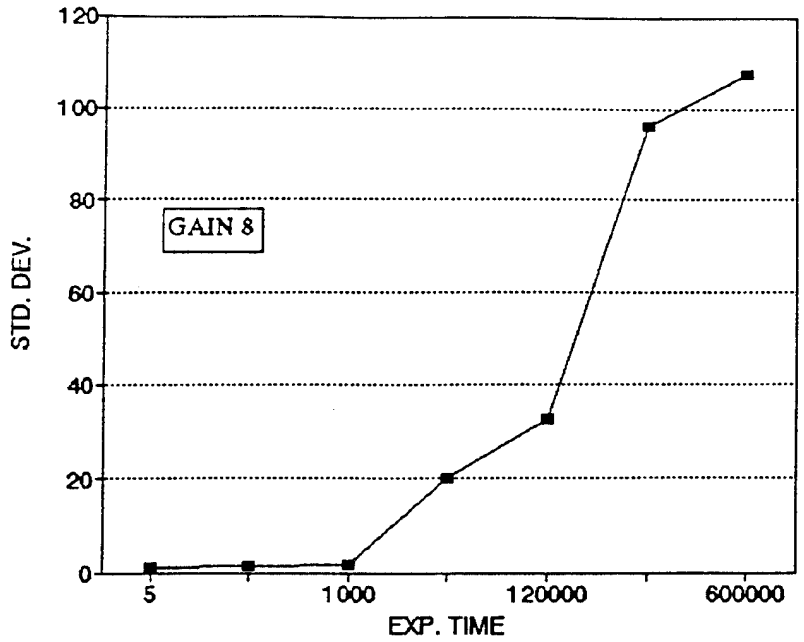

Figure 19: System Noise Standard Deviation as a Function of Exposure Time

The noise variation across the focal plane was evaluated using the repeatability data. There were three data sets collected. The collection parameters were:

Image Intensifier Temperature	20°C @
Exposure Times	250 msec & 60 sec
Gain	8
Image Intensifier Temperature	-20°C @
Exposure Times	250 msec
Gain	8

There were ten frames of data collected in each data set. Each frame was divided into five areas, the upper left, upper right, lower right, lower left and center. An array of 10 x 10 pixels were taken from each area of each frame. The pixels from each area of all frames were combined and statistically evaluated. Table 12 lists the mean and standard deviation obtained.

As can be seen there is no statistically significant variation in the noise across the detector plane for the cold temperatures and the shorter exposure times. One might make the case that the standard deviation is higher at the lower portion of the detector plane at the higher temperatures, however, at the shorter exposure times this variation is still insignificant. At the higher exposure times the increase is more significant in that the mean is 10% higher at the lower part of the detector plane and the standard deviation is nearly

doubled. This must be evaluated and accounted for in light of the uniformity of signal response across the detector plane.

Table 12

Focal Plane Noise Variation

AREA	TEMP °C	EXP. TIME Sec	MEAN Counts	STD. DEV. Counts
UL	-20	0.250	100.86	1.11
UR	-20	0.250	100.82	1.06
LR	-20	0.250	100.80	0.99
LL	-20	0.250	100.93	1.08
C	-20	0.250	100.80	1.08
UL	20	0.250	100.79	1.24
UR	20	0.250	100.71	1.11
LR	20	0.250	100.75	1.87
LL	20	0.250	101.08	1.92
C	20	0.250	100.55	1.04
UL	20	60.0	269.10	12.36
UR	20	60.0	274.35	13.40
LR	20	60.0	297.71	26.07
LL	20	60.0	301.74	22.52
C	20	60.0	271.01	14.80

Quartz Lamp Source Characterization

To assure that a calibration conducted at one location or time can be related to a second calibration, it is necessary to evaluate the repeatability and stability of the source to be used and the manner in which it will be used. Data sets were collected with the quartz lamp source illuminating the entrance slit and operating with currents of 7.8 Amps and 7.9 Amps. Three frames were taken at both power settings. The ratio of the three frames were obtained and then the mean and standard deviation were obtained. This provided the signal variation in the test set-up, including the source and detector instabilities. With a mean of 1, the test set-up would be stable with the noise given by the standard deviation. A change in source current of 1.26% from 7.9 Amps to 7.8 Amps generates a change in output counts of 8.34%. Data frames collected at a source current of 7.9 Amps at time intervals of 0,5 and 10 minute intervals provide information on the drift of the source and detection system. The change in the output after 5 minutes was a little under 0.4%, after

10 minutes the change was 1.3%. The source current can be maintained to within 0.01 Amp. When the source was turned off and then reset, the variation in counts out at each of three resets was less than 1%. Thus the error to be expected from source variation due to current control and drift is about 1%.

Diffusion Screen Evaluation

The diffusion screen used in the characterization and calibration tests is a highly reflective lambertian screen of spectralon. The screen was tested for its lambertian qualities over screen to source and screen to sensor variation of ± 15 degrees in both vertical and horizontal axes. The results show that the screen is lambertian to within 1%.

Gain Characterization

It is necessary to determine the system response as a function o the image intensifier gain setting. The test set-up used to determine this is shown in Figure 20. The test configuration parameters were as follows:

Grating	3600 gr/mm
Wavelength	500 nm
Exposure Times	250 msec
Slit Width	100 microns
Gain Settings	0 - 10
Gain Increments	0.5
Temperature	-16°C

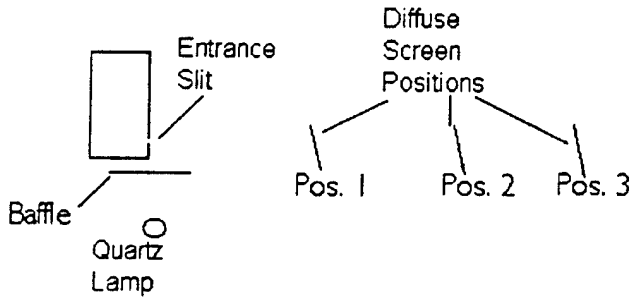

Figure 20: System Response as a Function of Gain Setting Test Set-up

Three frames of data were collected at each gain setting. The quartz lamp source illuminated the lambertian diffusion screen. Data were collected at increasing gain settings. Data were collected with screen in position 1 until saturation occurred. The gain

was then lowered by 1.0 and the screen moved away from the entrance slit until a mean of approximately 1600 counts was obtained. This screen was designated position 2. Data collection was then continued with increasing gains until gain saturation again occurred. The screen was again moved as before to position 3 and data collection continued. The data were the reduced to the mean of each frame. The overlap data points that were collected at each source move were corrected such that the instrument output is continuous. The normalized output as a function of gain is given in Figure 21.

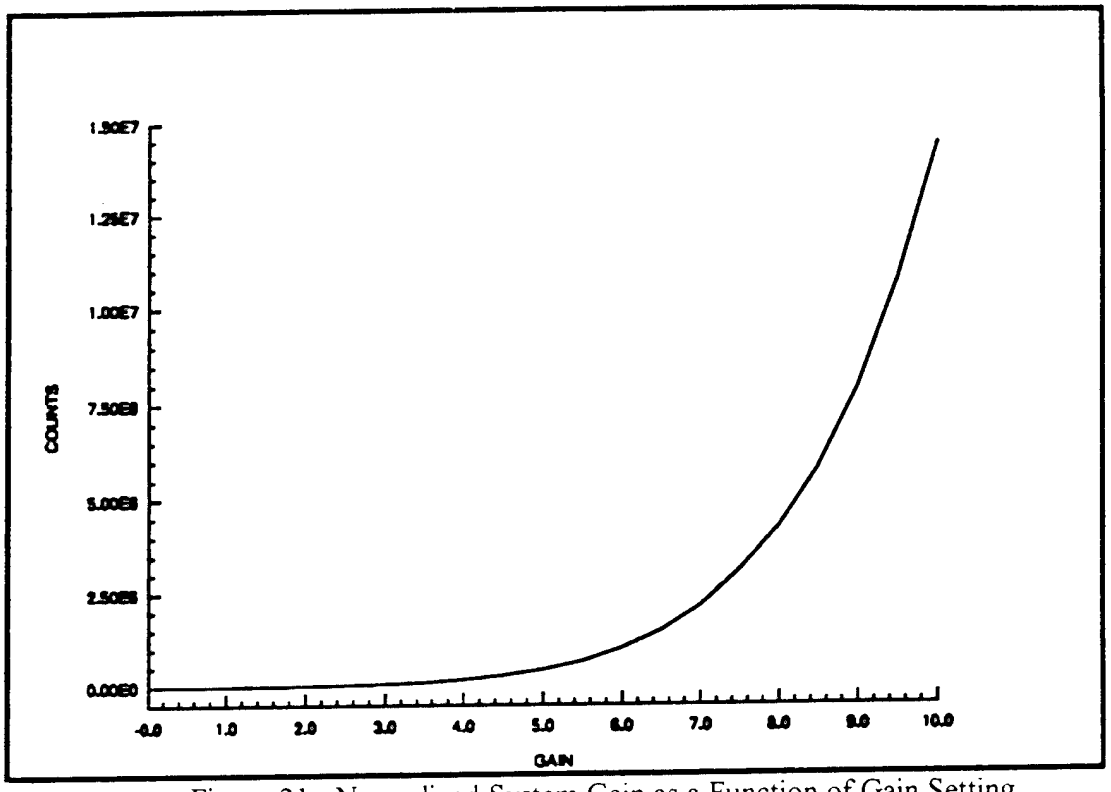

Figure 21: Normalized System Gain as a Function of Gain Setting

System Dispersion

The system spectral resolution will be limited by the dispersion of the system. The dispersion was determined at three wavelengths over the operating range of the system. The gratings were set at center wavelengths of 253.4, 435.8 and 696.5 nm for dispersion determination. The sources used were the Hg lamp for the 258.5 and 249.4 nm lines at the short wavelength limit, the 365 and 435.8 nm lines for the middle wavelength, and the Argon lamp for the 698.2 and 695 nm lines at the longer system wavelength. The upper operational limit of the 3600 gr/mm grating is 500 nm thus dispersion and focal plane coverage for this grating could not be obtained at the upper wavelength of 696.5 nm.

The results of system performance is given in Table 13. It can be seen that the dispersion is nearly constant over the operating range for the 147.5 through the 1200 gr/mm gratings. The system resolution is defined by requiring a minimum of three pixels to separate and identify two lines. This provides a pixel at the peak of each line and a pixel between the line peaks to identify line separation. With this definition the maximum system resolution is then the equivalent of three pixel dispersion. The resolution of the system is further reduced by the spreading of the image intensifier. The specifications of the image intensifier show that the spread in the intensifier will further reduce the resolution capability of the system to 40%. The resolution given in Table 13 was calculated using the mean of the dispersion of the grating listed. This mean was then used to determine the resolution of three pixels and then degraded to 0.40 due to the image intensifier.

The detector focal plane array consists of 578 columns of pixels in the spectral axis. The spectral coverage of the detector array will vary as a function of grating and center wavelength selected. The focal plane coverage can be obtained by multiplying the grating dispersion at the center wavelength selected by the available 578 pixel columns. As an example the 147 gr/mm grating has a dispersion of 0.305 nm/pixel at a center wavelength of 253.4 nm, as given in Table 13. Multiplying 0.305 by 578 gives the focal plane coverage of 176.3 nm as given in Table 14.

Table 13

System Capabilities

	Dispersion			Resolution (Calculated)
Grating g/mm	253.4 nm nm/pixel	435.8 nm nm/pixel	696.5 nm nm/pixel	(FWHM) nm
147	0.305	0.305	0.302	2.29
300	0.150	0.148	0.146	1.11
600	0.0738	0.0724	0.0702	0.54
1200	0.0360	0.034	0.0306	0.25
2400	0.0167	0.0138	0.0062	0.09
3600	0.0098	0.0053	N/A	0.06

Table 14

Focal Plane Coverage (FPC)

Grating gr/mm	253.4 nm FPC nm	435.8 nm FPC nm	696.5 nm FPC nm
147	176.3	176.3	174.6
300	86.7	85.5	84.4
600	42.6	41.8	40.6
1200	20.8	19.6	17.7
2400	9.6	8.0	3.6
3600	5.7	3.1	N/A

Grating Replacement Repeatability

The SpectraPro - 500 has the unique feature of a three grating turret in the system for use at any single time. The problem of characterizing a system with a turret in place and maintaining the characterization must be examined. Tests were conducted in which a turret was installed, removed and re-installed. With wavelength set at 0.00 nm, the column and row position of probe 10 on the detector focal plane was recorded at each installation of the grating turret to characterize the system repeatability in the removal and replacement of the turret gratings. Table 15 lists the recorded X and Y pixel positions of probe 10 for gratings 4, 5 and 6 after 7 removal and re-installations. Test conditions were:

Source:	Quartz Lamp
Probe:	10
Turret:	II (600, 2500 and 3600 gr/mm gratings)
Wavelength:	000.00 nm

This data, in Table 15 along with the dispersion data in Table 13, show that the repositioning with turret installation in the X or wavelength direction of the focal plane for grating 4 provides a wavelength shift of 0.07 nm, grating 5 a shift of 0.03 nm, and grating 6 a shift of 0.03 nm. These variations are less than the resolution of the system. Grating 6 shift is 1/2 the system resolution, grating 5 shift is 1/3 the system resolution and grating 4 shift is 1/8 the system resolution. As such the system wavelength performance and data interpretation are not significantly effected by the removal and re-installation of the grating turret. In the Y, or spatial direction the shift is 3, 8 and 8 pixels for 4, 5 and 6 respectively. This spatial shift will require a significant rewrite of the data reduction software. A probe can no longer be relied upon to illuminate the same 10 rows where initial calibration occurred. For this reason the decision was made to adjust the vertical position of the probes at every grating change such that the probe 10 output would be centered on row 185.

Operational Timing

To gather data during a test, the operational time of the data collection system must be fully understood. If the data collection system requires 40 sec to change from grating 1 to grating 3 but only 10 sec to change from grating 3 to grating 1 the test and data collection must be programmed to provide the maximum data with the minimum test time. The system timing capabilities are given in Table 16.

Table 15

Grating Turret Removal/Installation Performance

		Grating 4 (600 gr/mm)	Grating 5 (2400 gr/mm)	Grating 6 (3600 gr/mm)
Installation 1				
Position	X	288	289/90	292
	Y	178	187	176
Installation 2				
Position	X	289	289/90	292/93
	Y	183	186	174
Installation 3				
Position	X	288	289/90	292/93
	Y	183	186	174
Installation 4				
Position	X	288	289/90	293
	Y	183	186	175
Installation 5				
Position	X	288	289	292
	Y	183	187	173
Installation 6				
Position	X	288/89	290	290
	Y	180	180	180
Installation 7				
Position	X	288	288	289/90
	Y	180	178	181

Table 16

Operational Timing

Order Sorting Filters	1.4 sec between adjacent filters

Grating Change	Wavelength of Grating Change	
	0.0 to 0.0 nm	499.9 to 499.9 nm
	Sec	Sec
1 to 2	47.6	36.5
2 to 1	51.7	41.0
2 to 3	47.7	24.6
3 to 2	51.8	28.9
1 to 3	51.9	70.0
3 to 1	47.6	74.6

Changing the grating operational position follows the scan speed programmed into the controller. The maximum scan speed is given in Table 17 and must be included with these stated operational times for a complete calculation of the test time required to obtain a single data set.

It was noted in the testing that when a grating is changed and the grating speed is set, the next time the grating is called on the speed will automatically set to the original speed setting. It is therefore advisable to always set the grating speed to maximum. It is also noted that the grating speed will not go past the maximum speed or wavelength thus large grating speed can be input and the system will default to the maximum speed.

Table 17

Grating Performance

Grating #	Grating Spacing (gr./mm)	Linear Dispersion (nm/mm)	Maximum Scan Speed (nm/min)
1	3600	0.3	250
2	2400	0.5	375
3	300	6.4	3000
4	1200	1.5	750
5	600	3.1	1500
6	147.5	13.2	6000

Image Intensifier/Detector Array Uniformity

The response of the system is a function of wavelength and position of the incoming energy on the detector focal plane. The image intensifier cathode and the individual CCD detectors response are spatially non-uniform. To evaluate this non-uniformity the system was set with the following parameter:

Slit Width:	200 microns
Grating:	3600 gr/mm
Gain:	5
MCP Temperature:	-20°C
Wavelength Start:	250 nm
Wavelength Increments:	0.1 nm
Wavelength End:	256 nm

Sixty frames of data were collected to evaluate the variation across the focal plane due to response in wavelength. Frame 1 was divided by frame 59. This divides a frame of wavelength from 247 to 253 nm by a frame of wavelength from 253 to 259 nm. Ten rows at the top, middle and bottom of the resulting frame and the original frames 1 and 59 are then binned and the mean plotted. The results of this is shown in Figure 22.

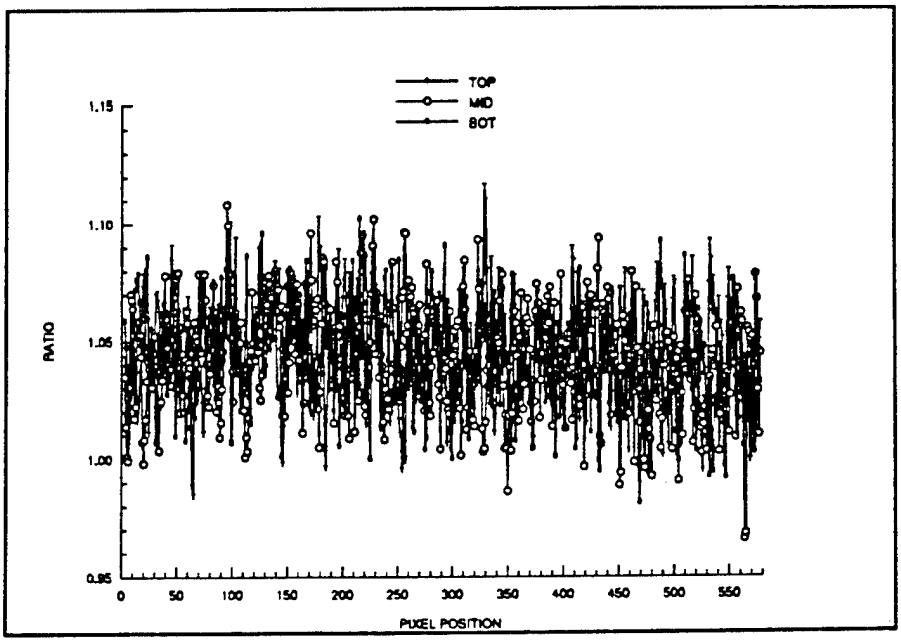

Figure 22: Variation in System Focal Plane Response as a Function of Pixel Position for a 6 nm Wide Focal Plane

This figure shows no variation across the data frame in either the wavelength or spatial position. This indicates there is no variation in response as a function of wavelength over this narrow wavelength interval. Variations other than wavelength have been divided out. Figures 23 and 24 show the binned data from frames 1 (wavelength 247-253 nm) and 59 (wavelength 253-259 nm). The variation shown here is due to response non-uniformity across the image intensifier and the detector array. This non-uniformity is under 10% and will be removed by the calibration data collected at every spectral window for every probe at each test data collection. This implies a requirement of calibration correction at each pixel and thus invalidates the use of a mean focal plane response.

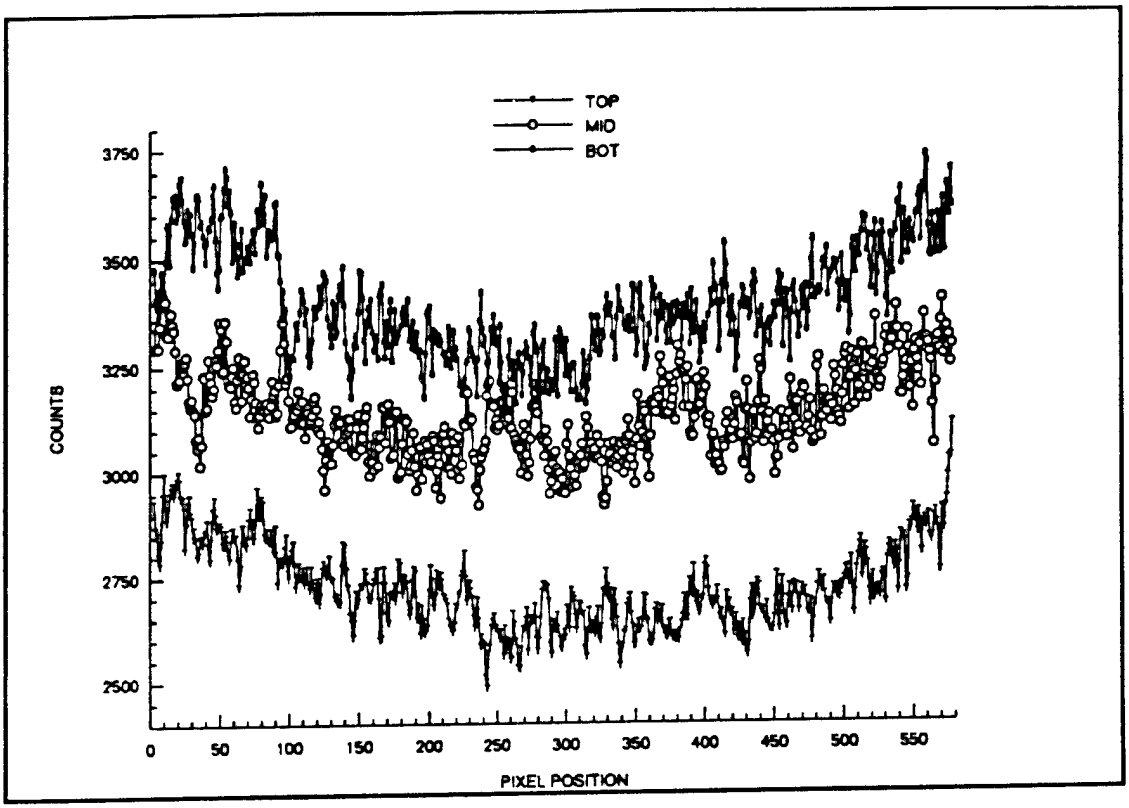

Figure 23: Focal Plane Relative Response as a Function of Pixel at Three Focal Plane Spatial Locations Frame 1

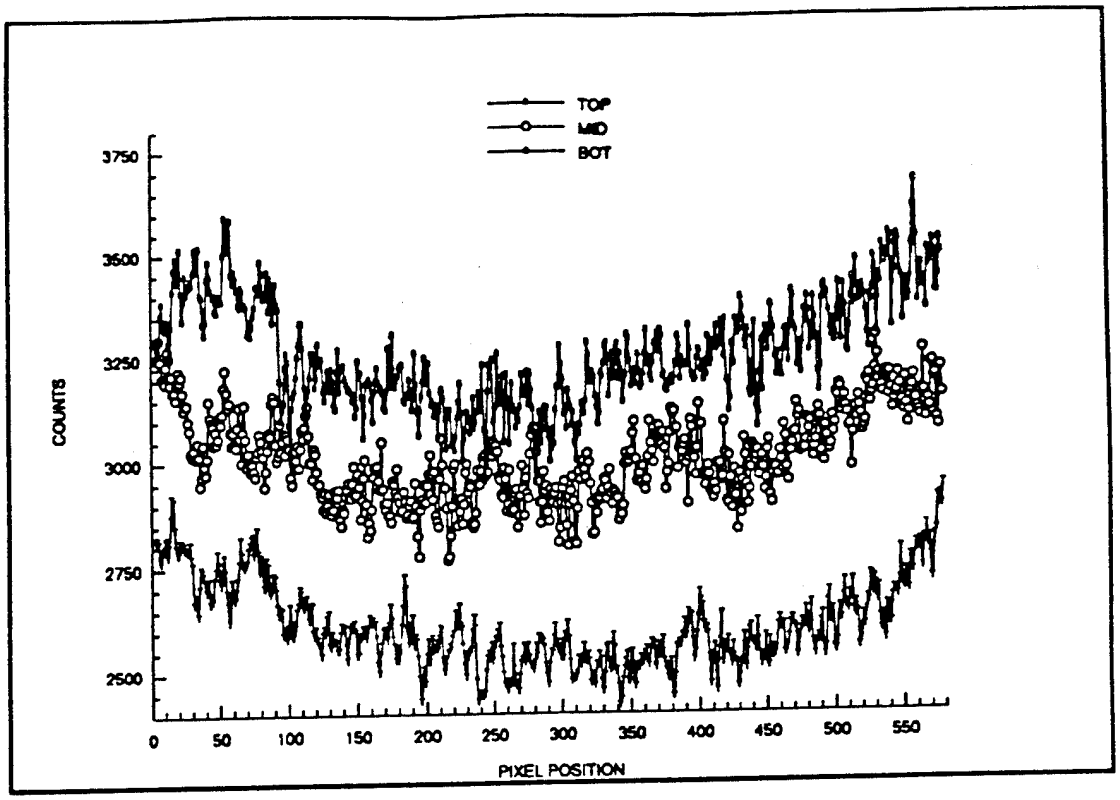

Figure 24: Focal Plane Relative Response as a Function of Pixel at Three Focal Plane Spatial Locations Frame 59

Probes Field of View

The field of view (FOV) of probes 4, 6, 8, 10, 12, 14 and 16 were measured after probe assembly and alignment. The measurement set-up for obtaining the FOV is shown in Figure 25. An alignment laser was used to position the quartz lamp enclosure pin hole in the middle of the probe image. The probe was then rotated about the probe aperture using the positioning table. The probe angular position and relative signal strength were recorded.

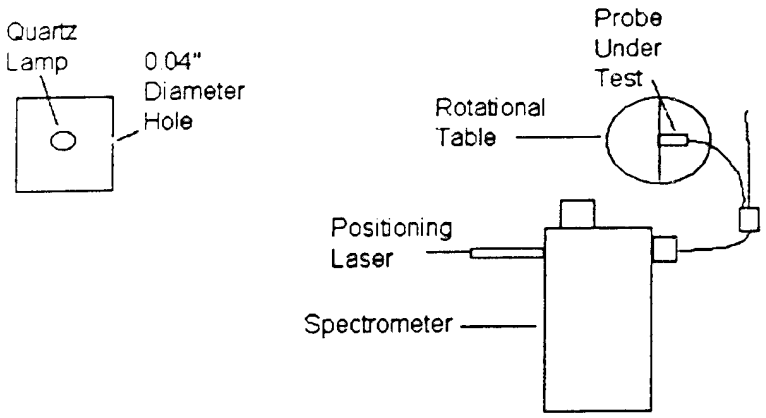

Figure 25: Probe FOV Test Set-up

Two FOV were obtained 90 degrees apart. One series was obtained on Probe 8 at 0, -90 and +90 degrees to evaluate FOV symmetry. The full width half power (FWHP) FOV of all probes fell within a 4 arc minute spread. Five probes had FOV's of 16.0 are minutes. Ten probes had FOV's within one arc minute of the maximum probe FOV frequency of 16 arc minutes. The roll off of the probes FOV has a nominal value of 4 arc minutes between the 20 and 80 percent points. For calibration and data reduction purposes the value of 16 arc minutes FWHP will be used. Figure 26 gives the frequency plot of the FWHP of 18 probes. Figure 27 shows the plot of Probe 8 measured FOV at three optical axis rotational positions, 0 Deg, 90 Deg (CW) clockwise rotation and 90 Deg (CCW) counter-clockwise rotation. This plot is typical of the probes measured. With 16 arc minutes FOV the spatial resolution of the system collection area expands at a rate of approximately 0.005 inch for every inch the target is located from the probe aperture. Thus at 12 inches the spatial resolution will be the aperture diameter of 0.5 inches plus 0.06 (0.005 x 12 inches) inches or 0.56 inches.

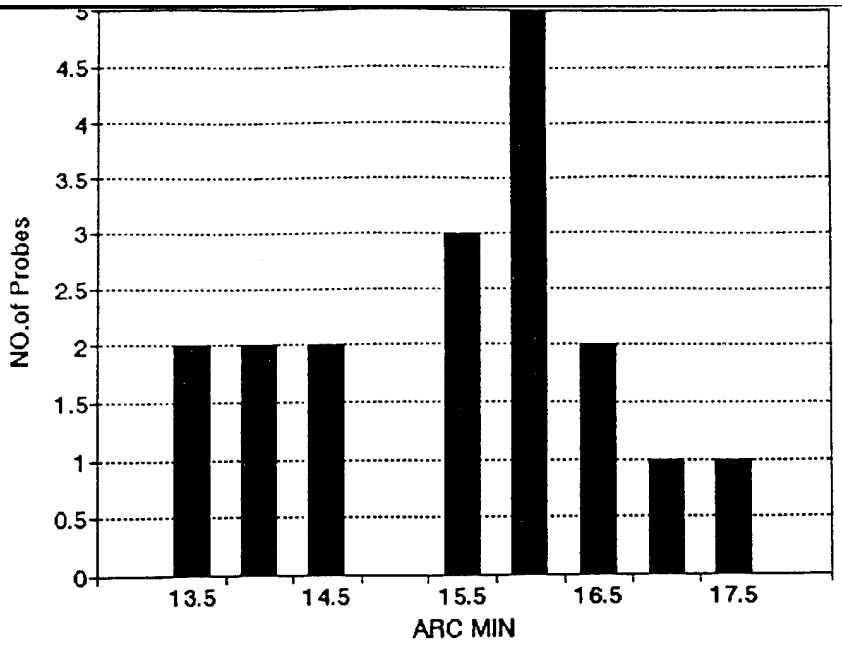

Figure 26: Probe FWHP Frequency Plot

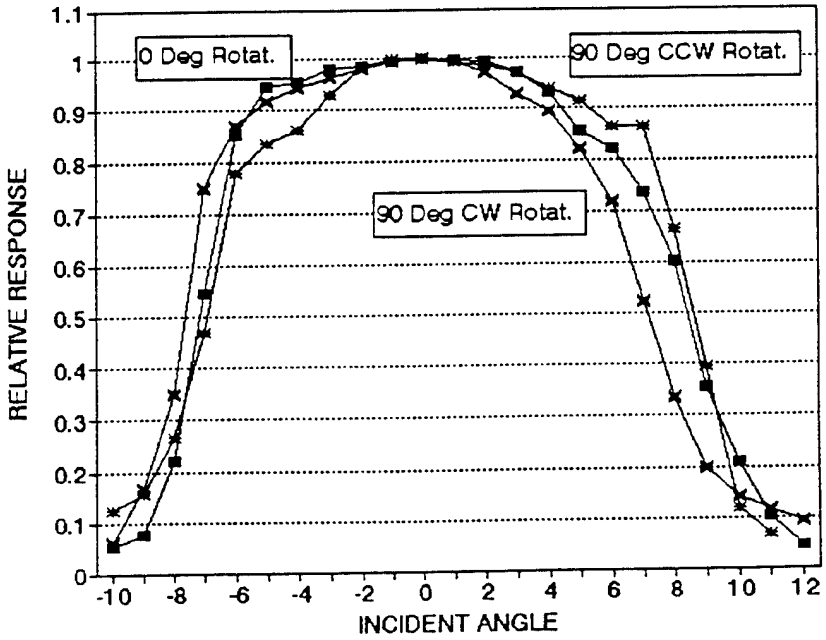

Figure 27: FOV Plot of Probe 8 at 0, 90 Deg CW, and 90 Deg CCW Rotation About the Probe Optical Axis

Exposure Time Linearity

Figure 28 shows the test set-up for evaluation of the system output linearity with variations in the exposure time settings.

Figure 28: Exposure Time Linearity Test Configuration

The source current was adjusted to provide an output below saturation at an exposure time of 500 msec. This current was then maintained from an exposure time of 5 to 600 msec. The changing of the source current to maintain signal levels within the system dynamic range, while changing the gain setting, does not allow data evaluation between the various gain settings. This does not restrict the evaluation of the system linearity within a set gain. The system linearity can be evaluated within the data collection of any one gain setting. Table 18 provides probe 10 output as a function of exposure time for gain settings from 0.0 to 10.0. The column headings are labeled as P(X)G(Y). The G(Y) provides the gain settings for the data collection and P(X) depicts the relative position the diffuse screen from the source and probe. As the gain is increased the output was maintained at a reasonable signal to noise level by changing these relative positions. Figure 29 provides an indication of the system linearity as a function of exposure time for all gain settings. This plot was derived by using the ratio of the system output within each gain setting, that is the system output at an exposure time of 10 msec was divided by the output at 5 msec, the output at 15 msec was divided by the 10 msec output continuing until all consecutive outputs were ratioed. The exposure times were then ratioed in the same manner, (i.e. 10 msec divided by 5 msec). The ratio obtained from the system output was then divided by the exposure time ratio. If the system is linear, this final division will produce a number equal to one. As can be seen in Figure 29, within the noise limit the system is linear with exposure time. All gains have a significant fluctuation at 5 msec where the output signal to noise is poor, and the curve with the highest fluctuation across the exposure time extent is produced with a system gain of 10 where the total system noise is greatest.

Table 18

Exposure Time Data

E-TIME	P0G0	P0G2	P0G4	P0G6	P1G6	P1G7	P1G8	P1G10
5	29.02	61.47	51.95	32.35	63.68	72.13	61.06	81.43
10	75.55	136.02	96.82	133.98	142.68	184.04	200.32	98.82
15	106.57	188.34	182.80	147.02	201.40	238.44	262.98	217.98
20	158.93	241.89	237.64	202.95	255.98	364.11	348.53	414.09
25	209.00	298.68	288.41	234.23	304.73	376.75	292.16	366.40
30	252.02	357.00	344.55	347.85	403.23	409.83	450.90	543.00
40	324.67	466.55	435.98	439.59	557.38	523.88	582.50	489.05
50	403.96	586.43	636.04	516.71	676.06	717.65	725.23	510.59
75	602.46	989.92	833.02	797.88	1034.02	956.32	976.25	728.13
100	809.35	1311.25	1232.17	1093.19	1328.69	1311.71	1334.25	1118.10
125	1026.10	1666.04	1546.19	1344.82	1699.80	1709.98	1723.18	1762.75
150	1247.08	2026.56	1860.21	1596.46	2070.92	2108.25	2112.10	2407.40
200	1709.02	2733.81	2460.67	2110.31	2536.84	3201.68	2484.02	3101.29
250	2177.15	3485.06	3204.21	2728.71	3441.73	3698.38	3277.15	3758.45
300	2665.94	4228.67	3897.81	3246.48	4328.69	3914.45	3656.07	3464.00
400	3678.35	5785.00	5236.50	4391.71	5755.12	5379.34	5293.08	6398.74
500	4703.90	7341.33	6673.40	5427.38	7364.04	8272.05	5787.84	7093.04
600	6595.02	8897.66	8110.30	6918.54	8972.96	11164.76	6282.60	7787.34

System Response

The total system response is a compilation of the response of the probe optics, probe fiber optics, image intensifier, monochromator and CCD array. Each element could be measured and then convolved into the system response. This approach compounds the system errors and effects of noise. The system response discussed here is a response measurement conducted on the total system once assembled and aligned. The sources used to obtain system response were Hg for the 253.4 nm and 436.8 nm lines and Ar for the 696.54 nm line. The probes were sequentially inserted into a fixed probe holder attached to each source and the data collected. Figure 30 shows the probes' relative responses. The probes output were normalized to the output of probe 5 at 696.54 nm as this was the maximum output of all measurements. The 696 nm data were the series that positioned the probes in their sequence of increasing response. It is interesting to note that probes 8 and 6 are reversed in the position of increasing response at 435 nm and probes 8, 6 and 4 and 15, 9 and 16 are inverted at 253 nm. This appears to be caused by the variation in the image intensifier spectral response across the area of the intensifier.

This is no concern in the data inversion and interpretation since all probes are calibrated individually in each spectral window used in data collection.

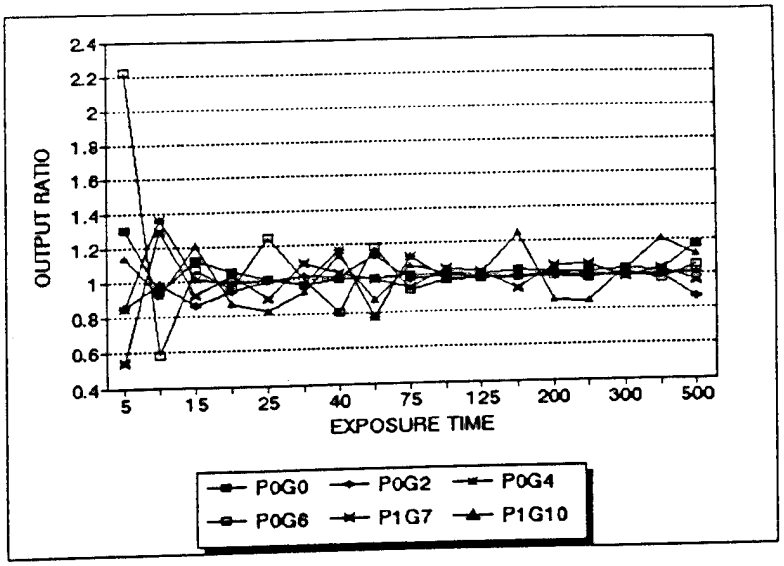

Figure 29: System Output Ratio as a Function of Exposure Time Ratio

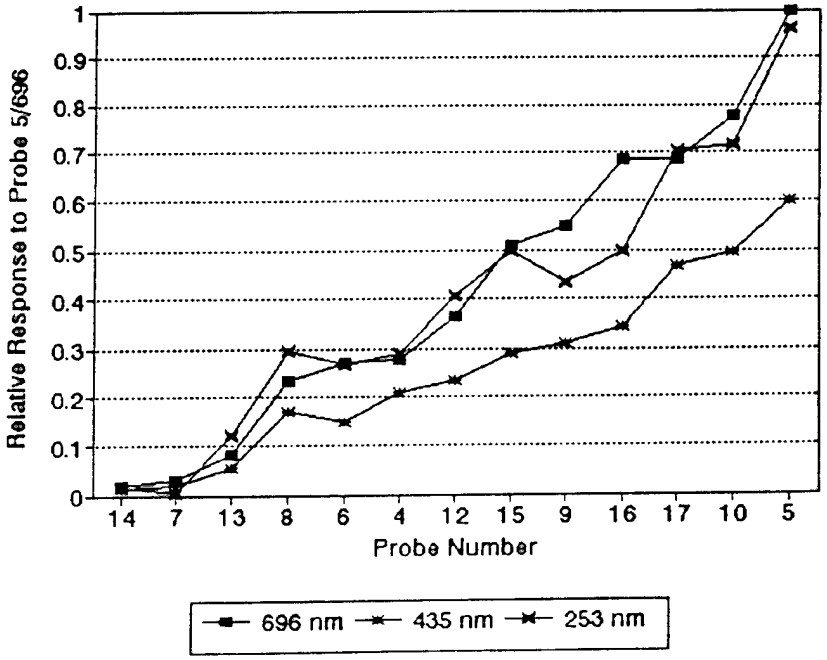

Figure 30: Probe Relative Response

SECTION IV: DATA COLLECTION/REDUCTION

Introduction

With the spectrometer imaging system characterized and initially calibrated, it is ready to be moved to the area for data collection. The move must be done carefully to assure no damage or significant change in the system operation occurs. If a significant change occurs it may be necessary to again characterize parts of the system, such as the probe FOV or alignment.

Test Definition

To adequately set up the data collection system and the test procedures, it is necessary to define the major data to be collected, determine the expected signal strength, and define the spectral content and resolution of the data desired. The resolution desired will determine the grating or gratings to be used in the data collection. The expected spectral content defines the spectral windows to be used in the collection of the data. The number of spectral windows to be used in data collection will go a long way in setting the length of test time required. The spectral windows will set the sequence of data collection with the sequence adjusted to provide the shortest test time through the order in which the windows are selected by the test operational software. The expected signal strength will determine the exposure time of each spectral window and thus complete the information required to set the final test duration. The test operational software is then written sequencing the grating, window selection and exposure time as defined in Section II. A test dry run without the target is performed to exercise the test operational software and accurately time the sequencing. This data collection time is then used to set the actual test duration and timing parameters.

Installation

The system must be placed close enough to the target for the fiber optics to span the distance between the target and the spectrometer input imaging optics. The fiber optics must be installed such that no strain is placed on any of the fibers or their termination. If the temperature variations at the data collection site are greater than approximately 10 degrees, it will be necessary for the system to be enclosed, insulated and conditioned air blown into the enclosure to stabilize the temperature. The 10 degrees is not an exact number, the temperature over which the system remains stable in its calibration and operation was not measured; it was just noted that when the sun heated the enclosure as the day began, the calibration taken early in the morning and the position of the probe output on the focal plane varied invalidating the calibration and grating/probe alignment. All spectral calibration line sources are placed in the enclosure. The spectral source holders contain the appropriate probe and neutral density filters. The filters are to assure no significant saturation in the spectral region of interest in the collection of data. A single switch is used to turn the spectral source lamps on and off. With the switch off, there should be no UVB or visible light entering the spectral calibration probes. The

system is now set up to quickly and easily collect a set of spectral calibration data. To do so the reference source lamps are turned on and the software that has been generated to set the spectral windows and proper calibration exposure times is run collecting spectral calibration data. A portable optical bench is set up to allow intensity calibrations of each probe on a routine basis. The set-up is similar to that shown in Figure 28. The calibration quartz lamp is set in a fixed position with a diffuse reflector screen set a distance of 50 cm from the lamp. A probe holder is placed in a position that allows the probes to view the diffuse screen filling the probe FOV and aperture. To assure lambertian test performance, the angle between a line perpendicular to the diffuse screen and a line from the diffuse screen to the probe axis or quartz lamp should not exceed 5 degrees. The intensity calibration set-up is enclosed such that external UV-visible radiation cannot enter the probes during calibration. Each probe is sequentially placed into the probe holder viewing the diffuse screen while the calibration software placed into the probe holder viewing the diffuse screen while the calibration software selecting the spectral windows and exposure times is run recording the calibration data for each probe in all data collection windows with the appropriate exposure time for the particular probe and data collection window. The system is now set to acquire test data. The data acquisition software described in Section II is now run to collect the desired data.

Data Collection

When one thinks of data collection there is a tendency to think only of the test data or data from the test source. It is necessary to think and understand the full program so that all necessary data are collected in a manner which will allow successful reduction and definition of the test data. Data defining the calibration sources will be required. Test set-up background data may be required. Data defining the various error sources in the characterization, calibration and test data collection will be required. Thus data collection begins early in the program well before the system is set up to collect the desired source test data.

Data Reduction

The reduction of test data is to provide data with engineering units. This usually follows standard reduction techniques. The radiometric intensity calibration of this system is normally conducted using a standard quartz lamp to translate the instrument output counts to radiometric quantities (Watts/cm^2-str-micron). Various reference line sources are used to translate the instrument image pixels to wavelength. The following series of steps are used in the reduction of test data:

1. Data Offset Correction:

Background data is collected for each probe at the beginning of each test. The background data frames may be acquired with different system integration times. The background data frames are reduced to a mean and standard deviation in counts. The mean intensity value of a background

data frame represents the offset value of the system at the particular integration time. These background data counts and their corresponding integration times are stored as an ASCII table in a file. The background offset value corresponding to an integration time of any data set can be either interpolated or extrapolated from this table.

2. System Response Calibration

To obtain a sensitivity measurement of each probe, traceable to a standard, each probe is set to view a standard quartz lamp reflected from a calibrated diffuse reflector. This data set is collected and stored as calibration data. Thus each intensity calibration data file contains the quartz lamp energy, collected in a spectral window via a data probe. The energy collected by the probe is dispersed across the focal plane. The spatial positions of the data probes on the CCD array detector can be determined as follows:

> For each intensity calibration data frame, 3 vertical strips are formed. Three 20-pixel wide strips are located at the left, center and right positions of the data frame, (as an example columns 5 through 25, columns 280 through 300 and columns 550 through 570 may be added together to provide the three vertical strips of a high signal to noise ratio). These 20-pixel columns are summed to form three single vertical line strips. These column strips are then examined as a function of row signal intensity. Peak intensity rows of the left, center, and right vertical line of strips are identified as the center rows or positions of a data probe in a spectral window (as an example the peak intensity of probe 10 on the left vertical strip may be found on row 184, on row 185 of the center vertical strip, and on row 186 of the right vertical strip). The intensities of the signals in each row of the vertical line-strip are then normalized to its peak intensity. Moving up and down the line strip, from the center row, the rows having intensity values equal to or greater than 50 % of the peak intensity are identified as the probe rows to be summed to determine the probe output for the particular probe radiance input (as an example the 50 % points of probe 10 on the left vertical strip may be rows 181 and 186, on the center vertical strip rows 183 and 187 and on the right vertical strip rows 183 and 190). The final data probe range is based on the minimum array rows that incorporate all left, center and right 50 % rows in the line strips of a data frame. In the example given above for probe 10 the included rows would be from row 181 to row 190. These data probe ranges are applied to all data and are a function of grating and spectral window.

A calibration lamp power curve, a diffuse reflector reflectance curve, and the curve of any other element in the system (i.e. window or filter) are generated and convolved to provide a counts/Watts/cm^2-str-micron system response calibration conversion curve for each spectral detector column in the detector array for each operating spectral window. The calibration lamp and diffuse reflectance curves are generated from manufacturers supplied data. The other transmission curve may be required to be generated from data collected at the test site. The final signal intensity correction required is the normalization of the data due to variations in the exposure or integration times. The exposure time used in the response calibration data obtained from the quartz lamp must be the same as the exposure time used in the collection of the test data or the data must be normalized to remove the system variations due to exposure time differences.

3. Spectral Calibration

A spectral conversion factor for each detector column is obtained from the source spectral lines within the spectral window of data collection. The spatial positions, in terms of rows, of the reference probes signal on the CCD array were determined. The rows of the detector array that contained reference probe energy collected are summed. Based on a single dispersion factor across the focal plane, a spectra of calibration lamps output intensity versus pixel position is displayed. Based on known spectra of the spectral calibration lamps, a series of single peak spectra located evenly across the focal plane of each spectral window are determined and their corresponding pixel positions identified. Using the data sets of known wavelengths and their corresponding pixel positions for each spectral window, a best fit equation is generated that identified each pixel's spectral position. These spectral calibration equations are used on all collected data. If no spectral calibration data set exists for a particular grating window due to window spectral position and spectral width, an alternative process is used for spectral calibration. This process uses an experimental data set in place of the spectral calibration data set. Since center wavelength and spectral resolution of all spectral windows are known, the wavelength of test data can be approximated. With a set of theoretical spectra provided as a reference, the test data is matched to the theoretical spectra. The wavelength of the theoretical spectra and its corresponding pixel position of the test data spectra is curve-fitted and used for spectral calibration. For a test data frame that was collected in a spectral window that had not been calibrated, the test data frame wavelength calibration is provided by using the identified wavelength of the closest adjacent spectrally calibrated window plus an offset. The wavelength offset is the difference between the center wavelengths of the test data frame and the adjacent spectrally calibrated window.

The raw test data are reduced using the above defined reduction techniques. The background offset is subtracted from the raw pixel counts. The total test data counts from a single probe using the defined probe range are obtained. The system response calibration data is used to convert from counts to Watts/cm^2-str-micron. The proper wavelength calibration is applied to each pixel within a spectral window data set. The reduced data sets are stored in a reduced data directory. The header of the files defines the test data and the system data collection parameters.

In addition the equations of any curves used in the data reduction (i.e. quartz lamp irradiance, diffuse reflector screen reflectance, exposure time normalization and background) and the techniques used to generate the equations must be stored in a file for future modification and use.

System Error Sources

The error sources for each aspect of the experiment must be listed and combined for the total expected error in the data.

Some of the errors associated with the calibration of an instrument such as this are as follows:

1. Error in the spectral calibration of the quartz lamp source from the manufacturer. This error is a bias in that the error is set at the time of calibration and is not a plus or minus as a function of time. This error is difficult to quantize without a full evaluation of the manufacturer's calibration technique. It will be assumed that the technique used follows the NITS standards and thus can be expected to have an accuracy of $\pm$ 5 percent.

2. Error due to an incorrect setting of the power to the quartz lamp. This is measured during the instrument laboratory test.

3. A curve is generated to fit the calibration data provided with the quartz lamp. This curve reproduces the data provided to some accuracy.

4. The reflectance of the diffuse screen is provided by the manufacturer to an accuracy.

5. A curve is generated to fit the reflectance data. This analytical expression retrieves the provided data points to some accuracy.

6. Error due to variations in positioning of the reflective screen. The diffuse reflective screen reflectance variation as a function of operational angle with the quartz lamp and the instrument input must

be measured over the expected angle of use.

7. The data reduction technique defined uses a linear relationship in the normalization of the data for variations in the exposure time. Thus if the exposure time were doubled for data point 2 from data point 1, data from point 2 is divided by two for comparison to data point 1. All reduced data have been normalized for variations in exposure time. Characterization tests must be conducted to define the error in the linearity assumption.

If the instrument slit width and gain were varied during the calibration and test, the error introduced for slit width or gain variations from calibration to test must be defined. Each probe FOV must be filled to the same extent and position in the FOV to eliminate the possibility of the introduction of an error due to non-uniform FOV response. The error in the positioning of the spectral lines is determined by spectral positioning error of the spectral sources in the particular window of interest.

These are some of the errors to be expected in the operation of this instrumentation system.

It is not intended that reduction procedures in this document be construed as the only way that the data collected by the spectrometer may be correctly reduced. This reduction procedure is to be used to generate a thought process and guidance in the reduction of the particular data gathered in future tests. The future tests may require all of the pretests discussed. Every test program must be thoroughly thought out with the necessary characterization and calibration tests identified and their procedures defined for the particular test.

APPENDIX

Manufacturer/Vendor	Address	Phone	Point(s) of Contact
C Technologies, Inc.	772 Bloomfield Ave. Verona, NJ 07044	(201) 239-4923 Fax: 239-4241	Robert Piretra
Princeton Instruments, Inc.	3660 Quakerbridge Rd Trenton, NJ 08619	(609) 587-9797 Fax: 587-1970	Ishi Nir (Hardware) Al Mottola (Hardware) Charlie Roberts (Software)
Acton Research Corp.	Box 2215 525 Main Street Acton, MA	(508) 263-3584 Fax: 263-5086	Dick Merk (Tech Sales) Bob Jarret (Engineering)
Gateway 2000	610 Gateway Drive N. Sioux City, SD 57049	(800) 248-2031 Fax: 378-2457	NA (Customer ID: Prince 13000)
Oriel Corporation	250 Long Beach Blvd. P.O. Box 872 Stratford, CT 06497	(203) 377-8282 Fax: 378-2457	Roger Melvie(?)
DataByte	11990 Hertz Street Moorpark, CA 93021	(805) 529-8795 (800) 253-2983 Fax: 529-9097	Steve Pollack
JANOS Technology, Inc.	HCR#33, Box 25 Route 35 Townshend, VT 05353	(802) 365-7714 Fax: 365-4596	Bradley Piccirillo